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# A linear programming approach for the optimal planning of a future energy system. Potential contribution of energy recovery from municipal solid wastes

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ABSTRACT

In the present paper the mismatch between the energy supply levels and the end use, in a broader sense, was studied for the Hellenic energy system. The ultimate objective was to optimize the way to meet the country's energy needs in every different administrative and geographical region using renewable energy sources (RES) and at the same time to define the remaining available space for energy recovery units from municipal solid waste (MSW) in each region to participate in the energy system. Based on the results of the different scenarios examined for meeting the electricity needs using linear programming and by using the exergoeconomic analysis the penetration grade was found for the proposed energy recovery units from MSWs in each region.

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**Contents**



## 1. Introduction

The problem of MSW management in Greece has reached a critical point due to the existing incomplete national planning. The problem of solid waste management is even more acute in urban and suburban centres, where most of the population resides and greater amounts of MSW are produced. The anarchic planning of renewable energy technologies distribution is certainly a hindrance towards the sustainable development of the Hellenic energy system. The ratio and the limits of installed capacity on each technology should be reviewed regularly and revised based on the implementation of new projects, and on the development of new technological applications. The main result of this study was that for the first time an innovative optimization tool was applied based mainly on linear programming which defined not only the optimal way to meet the country's energy needs using RES, but also could identify the size, the performance on energy recovery units from MSWs and their penetration into the Hellenic energy system. MSWs are by nature a very poor fuel, however Waste-to-Energy (WTE) units should be implemented firstly because of their ability to replace landfilling and associated environmental impacts and secondly because of their additional advantage of generating some electricity.

The proposed methodology could play a significant role in meeting the objective of Greece to satisfy 20% of its electric energy needs from RES by the year 2020 [1]. The country's energy system and the energy characteristics of each region were analyzed, and the best way to satisfy the energy needs in the carbon-free energy system based on low cost and high efficiency was determined. One of the basic outcomes of this research was to find out the remaining space for energy recovery units from MSW. This first section is the introduction; Section 2 includes important background studies on

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the field, Section 3 presents the methodology, Section 4 examines different scenarios and presents the results and Section 5 concludes.

## 2. Literature review

During the past decades, a large body of literature concerning the application of sophisticated energy optimization scenarios worldwide has been carried out. It includes studies concerning investigations of optimal use of energy in different countries and regions using different tools [2–6]. Grouping existing literature, there is a number of studies seem to be related on the optimization of the use of RES and the assessment of existing tools and the optimal penetration in autonomous power systems [7–10] and in the carbon-released energy systems [11–14].

Although numerous studies have been conducted on the optimization of electricity markets in order the system to function optimally in its present form, limited papers have appeared on the optimization of the carbon-released energy systems. Brand and Zingerle [15] have presented a study for Morocco, Algeria and Tunisia analyzing the impact of renewable energy integration into their power systems. Mazhari et al. [16] through system dynamics and agent-based modelling developed successfully an optimization methodology in order the most economical mixture of capacities of solar generation and storage to be obtained avoiding blackout from high fluctuating demand and unstable weather. Meibom and Karlsson [17] have stressed the role of hydrogen in the future Nordic power system, Brouwer [18], stated the role of fuel cells and hydrogen, as well, in the future energy system, while Lund et al. did point out the role of district heating in renewable energy systems [19]. Azzopardi and Mutale presented a methodology for modelling for assessing the viability of future PV systems and their integration into the energy systems. In fact it was proved that low efficient modules reduce the annual electrical energy costs for a end-user, compared to modern PV systems [20]. Koo et al. [21] and Kim et al. [22] examined different scenarios for costs and uncertainties that may affect the competitiveness of South Korea's renewable energy plan.

Besides, very limited review papers have appeared on energy recovery from MSWs as part of energy systems. Consonni et al. [23,24] presented different strategies for their exploitation, while Luoranen and Horttanainen [25] tried that in an integrated municipal energy supply system. Lupa et al. [26] and Touš et al. [27] were two groups that managed to study WTE plants in the frames of energy producing systems. However, it seems so far that there isn't an in depth integrated energy system study that defines the remaining energy space for MSWs to participate in the electricity generation process. In order the clear scientific gap related to energy system optimization and energy recovery from MSW, to be filled, this innovative study has been carried out.

## 3. Proposed methodology

The model used here, was designed to customize and quantify the implementation of available energy in each administrative region and to be taken into account for a sustainable future energy system. The technologies mainly used for the exploitation of solar energy are thermal solar energy systems (solar radiation in heat) and photovoltaic solar energy systems, geothermal energy, wind energy, hydropower and biomass.

The aim was to maximize the result of the objective function based on the "efficiency-to-cost" ratio. Using linear programming and specifically lindo software [28] a model has been developed to provide the initial optimal solution. Considering as an alternative energy source to the model energy recovery techniques from MSW, a new (and final) optimal solution was found. Under the new and final optimal solution for each case, a sensitivity analysis was implemented and a lot of scenarios were examined with many modifications in the availability of energy sources and how the system reacts on that. By applying an additional model it was found whether these proposed investments of energy recovery from MSW were viable or not.

**Table 1**
Unit costs from each energy source [€/kWh].

| RES | [€/kWh] | Reference |
|---|---|---|
| Solar collectors | 0.0453 | [34,35] |
| PV | 0.2 | [34,36] |
| Concentrated solar power (CSP) | 0.125 | [37,38] |
| Wind energy | 0.038 | [39–41] |
| Biomass | 0.08 | [42,43] |
| Geothermal energy | 0.106 | [44] |
| Hydro energy | 0.045 | [45,46] |
| Energy recovery from MSW | 0.04 | [47,48] |

The model of RES refers to various end uses such (end-uses categorized from Public Power Corporation [29]) as Domestic Use (DU), Industrial Use (IU), Commercial Use (CU), Agricultural Use (AU), Public Use (PU) and Lighting of Roads and Squares (LRS). Data were received from Public Power Corporation (PPC) for the years 2003–2009 [30].

The study reveals that cost and efficiency are highly critical factors in the use of RESs, and that factors such as technology, availability and reliability are considered in order to choose the appropriate RES for each end use. The average unit costs of each energy source (per produced kWh from each system) used in the optimization were selected from the literature in combination with authors' personal contacts with different utilities which either plan to invest in Greece or already operate units in Greece. It should be noted here, that in general in the country's regions in the mainland the average unit cost of each energy source was considered to be the same on average from region to region, as no significant variations were foreseen. On the contrary, in the insular regions the cost was significantly higher due to the interconnection costs (submarine cables, substations, AC/DC transformers etc.). Regarding the efficiency though, as it was normally expected, different efficiencies (capacity factor of the units) were selected for each region. Also, RES systems were used in the model to meet the electrical needs (and specifically solar collectors to save electrical consumption) and not to cover the heating needs at all. For instance, the capacity factor (CF) of a wind farm in the North Aegean region, where high wind speeds are in abundance, will be much higher than from a wind farm in Central Macedonia, where suitable sites for wind farms are absent [31]. Similarly, in Dodecanese islands solar radiation is significantly greater than any site in western Greece for instance, where sunshine is more limited [32]. On the other hand, Western Greece is richer in hydropower than any other area in Greece [33]. The above mentioned for the Greek regions are easy to be understood from the applications online Geographical Information System (GIS) tool for new RES projects, based on the capacity factor of the different projects in different regions (Fig. 1).

The unit costs from each energy source [€/produced kWh] used in the optimization model are shown in Tables 1 and 2.

As already mentioned, efficiencies of the energy systems used in the model are different. Depending on the examined region capacity factors and therefore efficiencies of units differ. This is every time declared on each different model used. In particular, solar thermal conversion collectors' efficiency is 30–40%, while for a PV park is 10–15% and for solar concentrators 25–30% [34,49,50]. Biomass units' efficiency ranges from 25 to 60% depending on the energy mixture (the low heating value of the combustible material, the humidity of the fuel, the homogenization of the mixture, etc.)

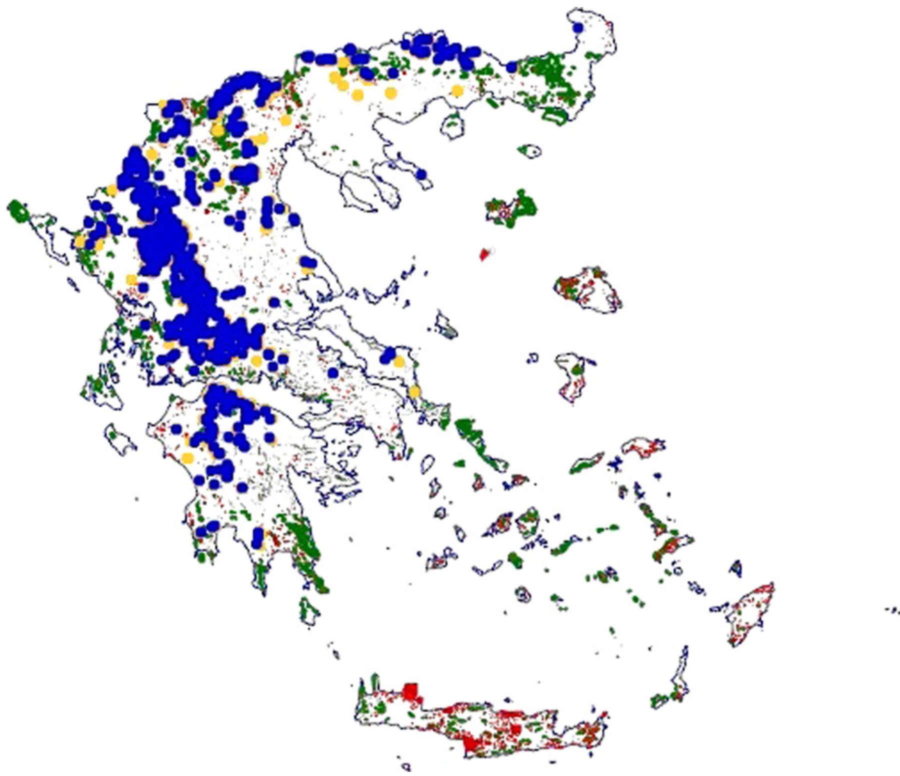

**Fig. 1.** Online GIS tool for new RES projects [53].

[42,51]. Geothermal units' efficiency is practically stable and lies around 80% [52–54]. The wind farms' energy efficiency was considered 20–38% [46,55–57] and the efficiency of a hydropower unit was considered to be 35–45% [58–60]. Finally, the efficiency of units of energy recovered from MSW estimated at 30% [61,62].

Using failure analysis, the reliability factors of the used renewable energy systems were calculated. These factors were taken as reliability constraints in the optimization renewable energy model for a reliable power supply. The reliability factors of 0.1 at 10,000 h for both solar systems, 0.5 at 10,000 h for wind and 0.9 at 10,000 h for biomass and geothermal energy systems, were used in the model [63–65]. Quantities of produced wastes and electricity consumption by region were collected from the Ministry of Development and the Public Power Corporation (PPC) [66–69]. The variables used in the model with all the nomenclature are presented in Table 3.

Variables $X_1$–$X_{44}$ represent the percentage of each energy system use shown in Table 3. The coefficients of the variables are based on the "efficiency/cost" ratio. The methodology was applied only for the optimum coverage of the electricity needs of the prefectures (the examination of partly or complete replacement of petroleum products from biofuels was not part of this research). After finding the best solution and depending on the availability of MSW and on their (energy recovery from MSW) contribution rate to in optimum solution, an exergoeconomic analysis was done in order to evaluate the proposed unit each time [70]. Also, it was considered in order to be realistic – as it is happening in other countries as well – that renewable energy sources can cover up to only 45% of the electricity needs. Large hydro plants and fossil fuels (lignite) and oil stations it is considered that cover country's major needs [71]. Furthermore, various scenarios that fit within profitable margins were extensively examined.

Applying sensitivity analysis, infinite scenarios could be examined on the utilization rate of each renewable energy system correspondence in the optimal model. These changes will affect the whole renewable energy system, meaning e.g. that when a renewable energy system is not in a position to contribute at its highest potential then other sources are chosen to cover this default by the system. The mathematical representation of the optimization model of is given in the following equations:

$$\text{Max}\left(A_j\sum_{i=1}^{2}X_i + B_j\sum_{i=3}^{8}X_i + E_j\sum_{i=9}^{14}X_i + F_j\sum_{i=15}^{20}X_i + D_j\sum_{i=21}^{26}X_i + C_j\sum_{i=27}^{32}X_i + G_j\sum_{i=33}^{38}X_i + H_j\sum_{i=39}^{44}X_i\right) \quad (1)$$

Subject to:

$$\sum_{i=1}^{2}X_i \le R_1, \quad (2)$$

$$\sum_{i=3}^{8}X_i \le R_2, \quad (3)$$

**Table 2**
Units' efficiency from different energy sources [%].

| RES | [%] | Reference |
|---|---|---|
| Solar collectors | 30–40 | [34,49,50] |
| PV | 10–15 | [34,49,50] |
| Concentrated solar power (CSP) | 25–30 | [34,49,50] |
| Wind energy | 20–38 | [46,55–57] |
| Biomass | 25–60 | [42,51] |
| Geothermal energy | 75–85 | [52–54] |
| Hydro energy | 35–45 | [58–60] |
| Energy recovery from MSW | 25–30 | [61,62] |

**Table 3**
Variables used in the model.

| Variable [%] | Source of energy for end-use |
|---|---|
| $X_1$ | Solar thermal collectors for Domestic Use (D.U.) |
| $X_2$ | Solar thermal collectors for Agricultural Use (A.U.) |
| $X_3$ | PV for Domestic Use (D.U.) |
| $X_4$ | PV for Commercial Use (C.U.) |
| $X_5$ | PV for Industrial Use (I.U.) |
| $X_6$ | PV for Agricultural Use (A.U.) |
| $X_7$ | PV for Public Use (P.U.) |
| $X_8$ | PV for Lighting of Roads & Squares (L.R.S.) |
| $X_9$ | Biomass for Domestic Use (D.U.) |
| $X_{10}$ | Biomass for Commercial Use (C.U.) |
| $X_{11}$ | Biomass for Industrial Use (I.U.) |
| $X_{12}$ | Biomass for Agricultural Use (A.U.) |
| $X_{13}$ | Biomass for Public Use (P.U.) |
| $X_{14}$ | Biomass for Lighting of Roads & Squares (L.R.S.) |
| $X_{15}$ | Geothermal for Domestic Use (D.U.) |
| $X_{16}$ | Geothermal for Commercial Use (C.U.) |
| $X_{17}$ | Geothermal for Industrial Use (I.U.) |
| $X_{18}$ | Geothermal for Agricultural Use (A.U.) |
| $X_{19}$ | Geothermal for Public Use (P.U.) |
| $X_{20}$ | Geothermal for Lighting of Roads & Squares (L.R.S.) |
| $X_{21}$ | Wind for Domestic Use (D.U.) |
| $X_{22}$ | Wind for Commercial Use (C.U.) |
| $X_{23}$ | Wind for Industrial Use (I.U.) |
| $X_{24}$ | Wind for Agricultural Use (A.U.) |
| $X_{25}$ | Wind for Public Use (P.U.) |
| $X_{26}$ | Wind for Lighting of Roads & Squares (L.R.S.) |
| $X_{27}$ | CSP for Domestic Use (D.U.) |
| $X_{28}$ | CSP for Commercial Use (C.U.) |
| $X_{29}$ | CSP for Industrial Use (I.U.) |
| $X_{30}$ | CSP for Agricultural Use (A.U.) |
| $X_{31}$ | CSP for Public Use (P.U.) |
| $X_{32}$ | CSP for Lighting of Roads & Squares (L.R.S.) |
| $X_{33}$ | Hydro for Domestic Use (D.U.) |
| $X_{34}$ | Hydro for Commercial Use (C.U.) |
| $X_{35}$ | Hydro for Industrial Use (I.U.) |
| $X_{36}$ | Hydro for Agricultural Use (A.U.) |
| $X_{37}$ | Hydro for Public Use (P.U.) |
| $X_{38}$ | Hydro for Lighting of Roads & Squares (L.R.S.) |
| $X_{39}$ | Energy recovery from MSW for Domestic Use (D.U.) |
| $X_{40}$ | Energy recovery from MSW for Commercial Use (C.U.) |
| $X_{41}$ | Energy recovery from MSW for Industrial Use (I.U.) |
| $X_{42}$ | Energy recovery from MSW for Agricultural Use (A.U.) |
| $X_{43}$ | Energy recovery from MSW for Public Use (P.U.) |
| $X_{44}$ | Energy recovery from MSW for Lighting of Roads & Squares (L.R.S.) |

$$\sum_{i=9}^{14} X_i \le R_3, \tag{4}$$

$$\sum_{i=15}^{20} X_i \le R_4, \tag{5}$$

$$\sum_{i=21}^{26} X_i \le R_5, \tag{6}$$

$$\sum_{i=27}^{32} X_i \le R_6, \tag{7}$$

$$\sum_{i=33}^{38} X_i \le R_7, \tag{8}$$

$$\sum_{i=39}^{44} X_i \le R_8, \tag{9}$$

$$X_1 + X_3 + X_9 + X_{15} + X_{21} + X_{27} + X_{33} + X_{39} \le R_9, \tag{10}$$

$$X_2 + X_6 + X_{12} + X_{18} + X_{24} + X_{30} + X_{36} + X_{42} \le R_{10}, \tag{11}$$

$$X_4 + X_{10} + X_{16} + X_{22} + X_{28} + X_{34} + X_{40} \le R_{11} \tag{12}$$

$$X_5 + X_{11} + X_{17} + X_{23} + X_{29} + X_{35} + X_{41} \le R_{12}, \tag{13}$$

$$X_7 + X_{13} + X_{19} + X_{25} + X_{31} + X_{37} + X_{43} \le R_{13}, \tag{14}$$

$$X_8 + X_{14} + X_{20} + X_{26} + X_{32} + X_{38} + X_{44} \le R_{14} \tag{15}$$

$$10\sum_{i=1}^{2} X_i \le R_1 \tag{16}$$

$$10\sum_{i=3}^{8} X_i \le R_2, \tag{17}$$

$$5\sum_{i=9}^{14} X_i \le R_3, \tag{18}$$

$$10\sum_{i=15}^{20} X_i \le R_4, \tag{19}$$

$$2\sum_{i=21}^{26} X_i \le R_5, \tag{20}$$

$$10\sum_{i=27}^{32} X_i \le R_6, \tag{21}$$

$$1.5\sum_{i=33}^{38} X_i \le R_7, \tag{22}$$

$$5\sum_{i=39}^{44} X_i \le R_8, \tag{23}$$

$$\sum_{i=1}^{44} X_i \ge 0, \tag{24}$$

The description of this model is the generic applicable form to all 13 administrative and geographical regions of the country. Depending on (a) the energy needs of each region, (b) the average efficiency of each renewable energy source unit in each region, and (c) the restrictions regarding the availability of each source, the model is better simulated in each different case. To fully understand the regional application 26 models - 2 for each region - were examined, the first one to identify the optimal solution in particular and the second one to determine up to what extent is the penetration possible of energy recovery from MSW units to be used in the system, and through a sensitivity analysis to quantify the correspondence of RES to fill the gap generated by the lack of one RES in the system. The efficiency coefficients are shown in Table 4, while it should be noted that the cost coefficients remain constant as shown in Table 1.

Each renewable energy source can cover maximum up to 45% of the electric consumption of the regions {constraints (2)–(9)}.

**Table 4**
Efficiency coefficients per each RES [%].

| Source of energy | [%] | Coefficient | Coefficient symbol |
|---|---|---|---|
| Solar collectors | A | A/0.0453 | Aj |
| PV | B | B/0.2 | Bj |
| Concentrated solar power (CSP) | C | C/0.125 | Cj |
| Wind Energy | D | D/0.038 | Dj |
| Biomass | E | E/0.08 | Ej |
| Geothermal Energy | F | F/0.106 | Fj |
| Hydro Energy | G | G/0.045 | Gj |
| Energy recovery from MSW | H | H/0.04 | Hj |

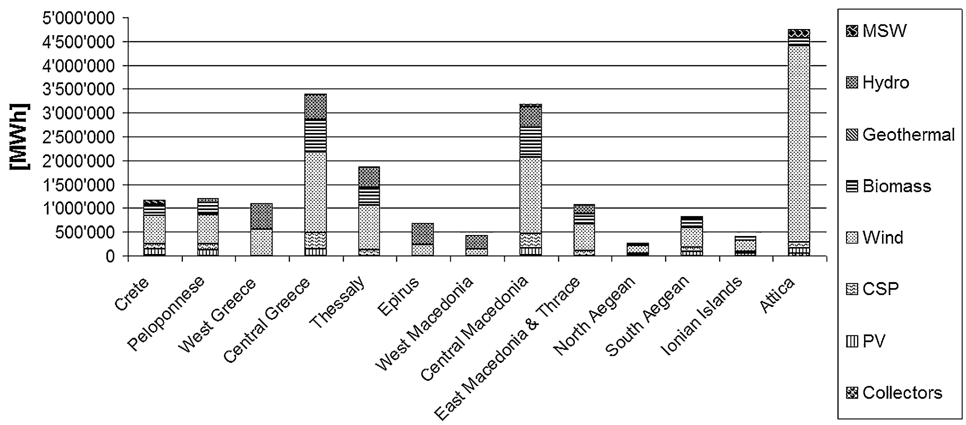


**Fig. 2.** Energy source participation in each region in [MWh].

For each different end-use an upper limit is set in the model for each region based on the consumption data received from PPC [69] {constraints (10)–(15)}. As mentioned above the reliability factors of 0.1 at 10,000 h for solar systems, 0.5 at 10,000 h for wind and 0.9 at 10,000 h for biomass and geothermal energy systems, were used in the model [62–64] {constraints (16)–(23)} and finally the non negativity of the used variables are inserted in the model using the constraint (24). Constants $R_{i,i=1-14}$ state the amount of energy each source can cover in each region ($R_1$–$R_8$) and the amount of energy each end-use requires (constants $R_9$–$R_{14}$).

## 4. Results

By solving the model for all regions a detailed optimal allocation for renewable energy sources is found for each one. In specific, through the use of the optimization model factors such as technology, availability and reliability were taken into consideration in order to choose the appropriate renewable energy source for each end-use. It can be easily seen (Table 5) that in half of the regions 45% of the electrical needs of the consumption were satisfied; while in others is just 40%.

It should be noted that these percentages correspond on the consumption of each region based on the data obtained from PPC [70]. Another series of models were set and used to optimize the use of energy including the energy recovery from MSW as an energy source that contributes in the energy scheme (Table 6).

It is obvious that now only three regions practically cannot cover 45% of their electricity need economically and efficiently, North Aegean, Ionian Islands, Attica regions. Fig. 2 shows graphically the share of each energy source in all regions in Greece.

As mentioned previously, a sensitivity analysis was implemented to quantify the response of the system to cover the potential gap in the absence of one RES or in the case that can contribute or participate to the energy mix up to a certain percentage of the total demand. Based on the results of this second model series the capacity of energy recovery units from MSW was defined in each region.

Different factors play role in the implementation of these units and through the exergoeconomic analysis (implementation of exergy analysis by applying economic principles in order to design more efficient units) which takes into consideration the minimization of the costs (operation costs, maintenance work, etc.) the city population, distances etc. the optimal sitting of these units is being optimized for all regions. Also, despite the fact that in some regions (West Greece, Epirus, West Macedonia) and after identifying the optimum solution for the system, an energy recovery from MSW unit it is not needed, yet based on the sensitivity analysis results for each case (maximum needed contribution from MSW's units on RES variation), back-up energy recovery from MSW units were proposed for a better control of the system (Table 7).

### 4.1. Renewable energy distribution model by varying all renewables potential

More analytically, for Crete and Peloponnese, for the solar collectors, because of their small contribution in the optimal solution, changes from 0 to 90% do not seem to affect the system (and the overall rate does not fall below 43.5%), while for biomass this percentage for zero contribution is 35% and for PV or CSP is 39.6%. Total predictably when wind energy is not contributing at all, only the 21.5% of the total 45% is covered and PV and biomass then contribute to cover wind's lack of presence.

For West Greece, Epirus and West Macedonia, on the lack of solar collectors practically nothing is happening, but in all three regions as wind energy and hydropower dominate, if one of the two could not contribute then on the lack of Wind the 2/3 are covered by hydro, biomass participates with 20%, CSP with 10%, and PV 1%, and MSW with 2%. Similarly, when hydropower is absent from the renewable energy scheme, wind covers half of the requested energy needs and the system still can cover 41.5% in all cases (of course when hydro "re-enters" the system with just 10% of its potential contribution, 45% can be covered).

For Central Macedonia, East Macedonia and Thrace, Central Greece and Thessaly regions, on the lack of solar energy (collectors, CSP and PV) practically the solution is not affected, while for biomass this percentage for zero contribution is 38–42% (depending on the region) and for hydro this percentage is more or less 41%. When wind energy is not contributing at all, only 25–26% of the total 45% is covered at all times with biomass and hydro (when available) units to take the lead role. 45% is being achieved only when wind energy is re-entering the system with overall contribution over 80%.

For insular regions as North Aegean, South Aegean, and Ionian Islands regions, the lack of hydropower energy offers all other energy sources a lead role. When collectors are absent, to the optimal solution is not affected, but when CSP and PV are not participating at all the overall coverage varies from 36% to the Ionian Islands to 39% to south Aegean where solar radiation levels are higher than any other part of Greece. For Biomass' zero contribution this percentage is 32–34%, while when wind energy is not contributing at all, only 18–20% of the total amount is covered at all times.

Finally, for Attica region on the lack of collectors practically nothing is happening, for CSP and PV or biomass this percentage

**Table 5**
Renewable energy scheme for each region.

| VAR | Crete | Peloponnese | West Greece | Central Greece | Thessaly | Epirus | West Macedonia | Central Macedonia | East Macedonia & Thrace | North Aegean | South Aegean | Ionian Islands | Attica |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *X*1 | 0.006 | 0 | 0.004 | 0.001 | 0.002 | 0 | 0 | 0.003 | 0 | 0 | 0.002 | 0.002 | 0.003 |
| *X*2 | 0 | 0.003 | 0 | 0 | 0 | 0 | 0 | 0 | 0.001 | 0.004 | 0 | 0 | 0 |
| *X*3 | 0 | 0.033 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.045 | 0.045 | 0.045 | 0.007 |
| *X*4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.008 | 0 | 0 | 0 | 0 |
| *X*5 | 0.040 | 0 | 0 | 0 | 0 | 0 | 0 | 0.016 | 0 | 0 | 0 | 0 | 0 |
| *X*6 | 0 | 0 | 0 | 0.020 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*7 | 0.005 | 0 | 0 | 0 | 0 | 0 | 0 | 0.012 | 0 | 0 | 0 | 0 | 0 |
| *X*8 | 0 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*9 | 0 | 0.090 | 0 | 0 | 0.064 | 0 | 0 | 0 | 0.090 | 0 | 0 | 0 | 0.009 |
| *X*10 | 0.090 | 0 | 0 | 0 | 0 | 0 | 0 | 0.090 | 0 | 0.083 | 0.090 | 0.090 | 0 |
| *X*11 | 0 | 0 | 0 | 0.090 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 0 | 0 |
| *X*12 | 0 | 0 | 0 | 0 | 0.014 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*13 | 0 | 0 | 0 | 0 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000 |
| *X*16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.023 | 0 | 0 |
| *X*17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*21 | 0.105 | 0.057 | 0.161 | 0.046 | 0.035 | 0.027 | 0 | 0.089 | 0.045 | 0.176 | 0.071 | 0.076 | 0.178 |
| *X*22 | 0.083 | 0.113 | 0.047 | 0.034 | 0 | 0 | 0.064 | 0.000 | 0 | 0.010 | 0.109 | 0.114 | 0.047 |
| *X*23 | 0.002 | 0 | 0 | 0.133 | 0.190 | 0.067 | 0.042 | 0.135 | 0.128 | 0 | 0.006 | 0.030 | 0 |
| *X*24 | 0.035 | 0.055 | 0 | 0.005 | 0 | 0.055 | 0 | 0 | 0.052 | 0 | 0 | 0 | 0 |
| *X*25 | 0 | 0 | 0.016 | 0.004 | 0 | 0 | 0.032 | 0 | 0 | 0.040 | 0.030 | 0 | 0 |
| *X*26 | 0 | 0 | 0 | 0.003 | 0 | 0 | 0.012 | 0 | 0 | 0 | 0.010 | 0.004 | 0 |
| *X*27 | 0.045 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.045 | 0.045 | 0.007 |
| *X*28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.017 | 0.006 | 0.045 | 0 | 0 | 0 |
| *X*29 | 0 | 0.038 | 0 | 0.045 | 0 | 0 | 0 | 0 | 0.007 | 0 | 0 | 0 | 0 |
| *X*30 | 0 | 0 | 0 | 0 | 0.028 | 0 | 0 | 0.022 | 0 | 0 | 0 | 0 | 0 |
| *X*31 | 0 | 0.007 | 0 | 0 | 0 | 0 | 0 | 0 | 0.024 | 0 | 0 | 0 | 0 |
| *X*32 | 0 | 0 | 0 | 0 | 0.006 | 0 | 0 | 0.006 | 0.008 | 0 | 0 | 0 | 0 |
| *X*33 | 0 | 0 | 0 | 0 | 0 | 0.144 | 0.208 | 0.059 | 0 | 0 | 0 | 0 | 0 |
| *X*34 | 0 | 0 | 0.059 | 0 | 0.071 | 0.129 | 0.042 | 0 | 0.077 | 0 | 0 | 0 | 0 |
| *X*35 | 0 | 0.031 | 0.098 | 0.069 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*36 | 0 | 0 | 0.053 | 0 | 0.027 | 0 | 0.049 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*37 | 0 | 0 | 0 | 0 | 0 | 0.017 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*38 | 0 | 0 | 0.011 | 0 | 0 | 0.009 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sum | 0.411 | 0.438 | 0.450 | 0.450 | 0.450 | 0.450 | 0.450 | 0.450 | 0.446 | 0.409 | 0.430 | 0.407 | 0.250 |

**Table 6**
Renewable energy scheme for each region including MSW.

| VAR | Crete | Peloponnese | West Greece | Central Greece | Thessaly | Epirus | West Macedonia | Central Macedonia | East Macedonia & Thrace | North Aegean | South Aegean | Ionian Islands | Attica |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *X*1 | 0.006 | 0 | 0.004 | 0.001 | 0.002 | 0 | 0 | 0.003 | 0 | 0 | 0.002 | 0.002 | 0.003 |
| *X*2 | 0 | 0.003 | 0 | 0 | 0 | 0 | 0 | 0 | 0.001 | 0.004 | 0 | 0 | 0 |
| *X*3 | 0 | 0.028 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.045 | 0.045 | 0.045 | 0.007 |
| *X*4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*5 | 0 | 0.005 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 0 | 0 | 0 | 0 |
| *X*6 | 0 | 0 | 0 | 0.017 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.012 | 0 | 0 | 0 | 0 | 0 |
| *X*8 | 0 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*9 | 0 | 0.090 | 0 | 0 | 0.064 | 0 | 0 | 0 | 0.090 | 0 | 0 | 0 | 0.009 |
| *X*10 | 0.090 | 0 | 0 | 0 | 0 | 0 | 0 | 0.090 | 0 | 0.083 | 0.090 | 0.090 | 0 |
| *X*11 | 0 | 0 | 0 | 0.090 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 0 | 0 |
| *X*12 | 0 | 0 | 0 | 0 | 0.014 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*13 | 0 | 0 | 0 | 0 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.023 | 0 | 0 |
| *X*17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*21 | 0.065 | 0.056 | 0.161 | 0.046 | 0.035 | 0.027 | 0 | 0.081 | 0.045 | 0.176 | 0.071 | 0.076 | 0.175 |
| *X*22 | 0.083 | 0.113 | 0.047 | 0.034 | 0 | 0 | 0.064 | 0 | 0 | 0.010 | 0.109 | 0.114 | 0.050 |
| *X*23 | 0.042 | 0 | 0 | 0.133 | 0.190 | 0.067 | 0.042 | 0.144 | 0.128 | 0 | 0.009 | 0.030 | 0 |
| *X*24 | 0.035 | 0.056 | 0 | 0.007 | 0 | 0.055 | 0 | 0 | 0.052 | 0 | 0 | 0 | 0 |
| *X*25 | 0 | 0 | 0.016 | 0.004 | 0 | 0 | 0.032 | 0 | 0 | 0.040 | 0.030 | 0 | 0 |
| *X*26 | 0 | 0 | 0 | 0.001 | 0 | 0 | 0.012 | 0 | 0 | 0 | 0.007 | 0.004 | 0 |
| *X*27 | 0.003 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.045 | 0.045 | 0.007 |
| *X*28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.017 | 0.013 | 0.045 | 0 | 0 | 0 |
| *X*29 | 0 | 0.032 | 0 | 0.045 | 0 | 0 | 0 | 0 | 0.007 | 0 | 0 | 0 | 0 |
| *X*30 | 0 | 0 | 0 | 0 | 0.028 | 0 | 0 | 0.022 | 0 | 0 | 0 | 0 | 0 |
| *X*31 | 0.036 | 0.013 | 0 | 0 | 0 | 0 | 0 | 0 | 0.024 | 0 | 0 | 0 | 0 |
| *X*32 | 0 | 0 | 0 | 0 | 0.006 | 0 | 0 | 0.006 | 0.001 | 0 | 0 | 0 | 0 |
| *X*33 | 0 | 0 | 0 | 0 | 0 | 0.144 | 0.208 | 0.059 | 0 | 0 | 0 | 0 | 0 |
| *X*34 | 0 | 0 | 0.059 | 0 | 0.071 | 0.129 | 0.042 | 0 | 0.077 | 0 | 0 | 0 | 0 |
| *X*35 | 0 | 0.031 | 0.098 | 0.069 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*36 | 0 | 0 | 0.053 | 0 | 0.027 | 0 | 0.049 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*37 | 0 | 0 | 0 | 0 | 0 | 0.017 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*38 | 0 | 0 | 0.011 | 0 | 0 | 0.009 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*39 | 0.082 | 0.006 | 0 | 0 | 0 | 0 | 0 | 0.008 | 0 | 0 | 0 | 0 | 0.004 |
| *X*40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*42 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *X*44 | 0.008 | 0 | 0 | 0.003 | 0 | 0 | 0 | 0 | 0.007 | 0.009 | 0.003 | 0.006 | 0.006 |
| Sum | 0.450 | 0.444 | 0.450 | 0.450 | 0.450 | 0.450 | 0.450 | 0.450 | 0.446 | 0.417 | 0.433 | 0.413 | 0.260 |

**Table 7**
Proposed units for energy recovery from MSW.

| Region and units | [MWh] | Capacity [MW] | Full payment period | IRR [%] |
|---|---|---|---|---|
| Crete | 78,506 | | | |
| Heraklion | | 19 | 10 | 12.2 |
| Chania | | 4.5 | 8 | 14.7 |
| Rethymnon | | 2.7 | 12 | 9.31 |
| Ierapetra | | 3.5 | 16 | 4.6 |
| Peloponnese | 15,581 | | | |
| Kalamata | | 3.5 | 13 | 8.1 |
| Korinthos | | 2.7 | 16 | 4.0 |
| West Greece | 0 | | | |
| (Patra) | | (7.5) | (11) | (11.4) |
| Central Greece | 19,025 | | | |
| Lamia | | 7.5 | 15 | 5.6 |
| Thessaly | 21,334 | | | |
| Larissa | | 8.5 | 11 | 11.5 |
| Epirus | 0 | | | |
| (Ioannina) | | (3.5) | (12) | (10.6) |
| West Macedonia | 0 | | | |
| (Kozani) | | (3.25) | (12) | (10.2) |
| Central Macedonia | 59,156 | | | |
| Thessaloniki | | 23.5 | 9 | 13.6 |
| East Macedonia & Thrace | 17,176 | | | |
| Kavala | | 6.75 | 10 | 11.8 |
| North Aegean | 5676 | | | |
| Mytilene | | 2.25 | 7 | 19.5 |
| South Aegean | 5622 | | | |
| Rhodes | | 2.25 | 8 | 16.5 |
| Ionian Islands | 5912 | | | |
| Corfu | | 2.25 | 9 | 13.4 |
| Attica | 182,557 | | | |
| Athens | | 46 | 11 | 12 |
| Total | 410,544 | 134.9[a] | 11.1[b] | 11.2[b] |

[a] Total in [MW] excluding the back-up units in Patra, Ioannina,and Kozani.
[b] Average excluding the back-up units in Patra, Ioannina,and Kozani.

is 25% (from 26% on the optimal solution), while for wind energy when is not contributing at all, only 3.5% is covered.

### 4.2. Exergoeconomic analysis

Exergoeconomics is a unique combination of exergy analysis and cost analysis conducted at the component level, to provide the unit designer or operator of an energy conversion system with information crucial to the design of a cost-effective system. Exergoeconomics is an exergy-aided cost reduction approach that uses the exergy costing principles. These principles state that exergy is the only rational basis for assigning economic values to the transport of energy and to the inefficiencies within a system. The ultimate objective of exergoeconomic optimization is to reduce the sum of capital-investment related costs, fuel costs and operating and maintenance expenses for the overall investment. Decisions are made, however, at the plant component level [72,73]. A complete exergoeconomic analysis consists of (a) an exergetic analysis, (b) an economic analysis, and (c) an exergoeconomic evaluation. In this research a wider and perhaps a more theoretical approach of exergy was introduced aiming in obtaining the maximum delivered output from each examined system as a whole.

Based on this concept, an exergy-based model was created to determine the "losses" of each proposed unit and to identify how productive and efficient a system could be. Therefore some general assumptions were taken for the implementation of the model. For instance it is considered that the opening hours of any unit per year is 8760 (365 days by 24 h), while for the transportation costs for the cities it was taken as 1.6 €/km/tn, while for rural roads it was assumed at 2.8 /km/tn [74]. Also, based on the efficiency of a thermal processing unit (~30%) [75] and the produced electrical kWh per tn, assumed 600 kWh per tn based on the "Waste-to-Energy" units study of the American Society of Mechanical Engineers (ASME) [76,77] were calculated the MWh, that could be obtained from each unit.

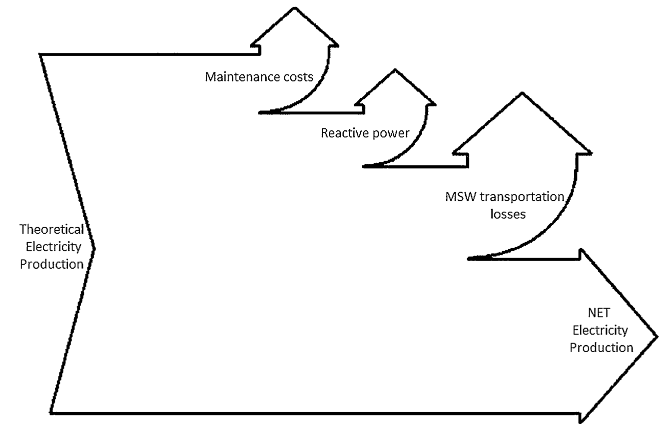


**Fig. 3.** Exergy losses from the operation of an energy recovery from MSW unit.

Sankey diagram (Fig. 3) shows exergy losses mainly due to maintenance work (such as personnel costs, produced ash selling costs etc.), losses due to energy consumption of sub-systems (reactive load), losses due to the transport of MSW. The production cost of kWh was considered to be 0.04 €, quite reasonable considering the overall project [47,48].

The interest rate is equal to 6.65%, the loan repayment period shall be 10 years with stable instalments of the loan plus the interest, income tax 25% and paid the same year [78], the selling price of produced kWh either 0.9945 €/kWh for islands or 0.8785 €/kWh for the mainland (in accordance with the law N.3851/2010) [79]. The operating and maintenance cost is 25 € per year per tn while the cost of selling the produced ash is 12 € per tn [80]. The transportation costs are 1.6 €/tn/km for distances close to the cities (<5 km) and 2.8 tn/km to greater distances (5 < $x$ < 15 km) [74]. Finally, are taken into consideration the profits from recovery of metals (about 1 kg per day for ferrous metals ~130 € per kg and 0.1 kg of aluminum per day for ~1300 € per kg) for a unit of 5 MW [80].

The funding scheme was every time chosen based on the new Draft Development Law on the "subsidization to private investment to promote economic and social development and regional convergence and other provisions" [81] and the results for the proposed investments and their profitability after the analysis are shown in Table 7. On the website http://www.uest.gr/ppt/EXERGOECONOMICS_eng.xls there is freely accessible an exergoeconomic tool developed, waiting as an input the results of the exergy analysis and some economical parameters in order to investigate the viability (and profitability) of any investment and contribute in the designing of a cost-effective and efficient system. The 19 MW Heraklion proposed unit was examined and the results are apposed, although the model can be stored and used for any unit.

## 5. Conclusions

Through this research a new concept in linear programming and exergoeconomics analysis was given which identified the optimal energy use (reducing losses) when designing a system. In a broader sense, this analysis could be regarded as a thermodynamic optimization analysis. An integrated attempt was done (a) to optimize renewable energy planning for the Hellenic energy system – for all different regions – and (b) to use energy recovery technologies of solid waste treatment with the best way, adapted to Hellenic system by combining these proposed units with the initial optimal planning.

The methodology developed used a method of systemic analysis (definition problem → mathematical modelling (multiobjective analysis) → optimal solution → sensitivity analysis on the operational parameters → exergoeconomic analysis → project viability). It turned out that in the three regions of Western Greece where hydro power is in abundance (and wind power as well) the proposed WTE units were not that necessary since they could cover the entire electricity consumption (up to 45%), while in any change in the system (lack of one or even two RES) it is strong enough to overcome this bereavement.

On the contrary, in Central and Eastern Greece (and mostly in the islands), the strong dependence on renewable energy showed the need for contribution of the proposed units of energy recovery from MSW of 135 MW in total, and how this could "support" at the end the Hellenic Transmission System Operator.

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